Performance Comparison of Spectrum-Slicing Techniques Employing SOA-Based Noise Suppression at the Transmitter or Receiver

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Abstract— **We compare three SOA-based noise suppression approaches employed in incoherent light spectrum-sliced systems. Although the SOA at the transmitter provides the best absolute noise suppression, it is susceptible to performance degradation in the presence of optical filtering and dispersion. Using the SOA at the receiver can provide good performance while avoiding these limitations, and may provide better value in last-mile access applications.**

Index Terms— **Optical noise, semiconductor optical amplifier, spectrum slicing, wavelength division multiplexing**

I. INTRODUCTION

SPECTRUM-sliced wavelength division multiplexing (WDM) is currently being investigated as an attractive and viable solution for 'end-user' passive optical network (PON) architectures, and capitalizes on the economic advantages of broadband sources such as light emitting and superluminescent diodes. Additionally, these 'thermal-like' incoherent sources offer the system advantages of reduced environmental sensitivity and low Brillouin scattering [1]. However, the intensity noise present in spectrum-sliced incoherent light increases with decreasing slice bandwidth and imposes an upper limit on the achievable signal-to-noise ratio (SNR) [2]. It has been shown that a gain saturated semiconductor optical amplifier (SOA) can be used to overcome this limitation and suppress the intensity noise, enabling significant performance improvements in spectrum-sliced systems [3]. The SOA has the added benefit that it can be monolithically integrated alongside other optical and electronic components, to provide a compact solution for access markets.

The saturated single-pass SOA efficiently suppresses the intensity fluctuations in the input light across a bandwidth determined by the device operating point and carrier lifetime, and can be used with channel bit rates as high as several gigabits per second. While the main focus of the research to date has been on using the SOA to reduce the noise of the continuous wave (CW) signal prior to modulation, other configurations employing the saturated amplifier at the receiver have also been proposed [4]–[6]. Incorporating the SOA at the receiver is an attractive alternative, as in addition to the noise reduction, the SOA also functions as a preamplifier, increasing the overall sensitivity of the receiver unit. However, when used to amplify a modulated bit stream, the saturated SOA introduces 'patterning', which distorts the input signal and degrades the overall system performance [7].

In [4], Kim et al. show that optically pumping the SOA by injecting broadband incoherent light reduces eye distortion due to patterning while retaining good noise suppression. Using this technique a 0.5 nm bandwidth spectrum-slice was transmitted at 2.5 Gb/s over 20 km, showing noticeable improvement over the standard spectrum-slicing approach with no SOA preamplifier. Alternatively, the gain modulation of a saturated SOA can be used to transfer the modulated data from the input spectrum-slice to the backward-propagating amplified spontaneous emissions (ASE) [5], thus avoiding the patterning effects which occur in the amplified forward-propagating signal. Using this approach, intensity noise reduction and receiver sensitivity improvements were demonstrated at 1 Gb/s with a slice width of 0.6 nm. Cross gain modulation within the SOA can also be used to transfer the data to a *coherent* carrier signal to facilitate wavelength routing and interconnection with WDM-based trunk networks. Using this approach, a 1.2 nm spectrum-slice was coupled to a counter-propagating beam from a DFB laser diode, achieving error free transmission at 2.5 Gb/s [6].

While each of these approaches has demonstrated significant improvement in signal quality, there has been no systematic comparison of the relative performance advantages provided by the various techniques. In this paper we present a performance comparison of spectrum-sliced systems employing incoherent sources in conjunction with SOA-based noise suppression and discuss the relative benefits and drawbacks of each technique. The system proposed in [6] is omitted from this comparison due to the addition of the coherent source at the receiver.

II. COMPARATIVE STUDY

The three techniques investigated in this study are referred to herein as *SOA at the transmitter* [3], *SOA ASE injection* [4] and *SOA ASE modulation* [5], block diagrams of which are given in Fig. 1.

We characterized the single channel performance of each system, both back-to-back and after transmission through 15 km of standard single mode fiber (SMF-28) [8]. The ASE of an erbium doped fiber amplifier was used as the broadband source and a fiber Bragg grating of 0.24 nm bandwidth (3 dB) was used as the input-slicing filter. System performance was assessed by measuring Q at a bit rate of 2.5 Gb/s using

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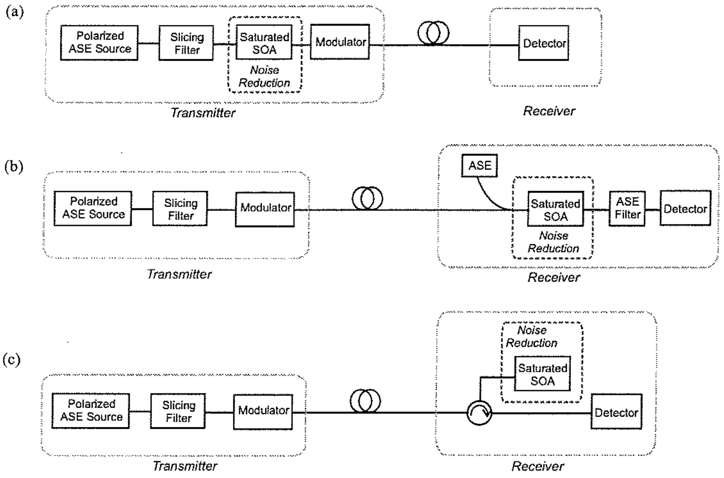

Fig. 1. Single channel block diagrams: (a) *SOA at the transmitter* (+5 dBm SOA input power, 200 mA drive current) (b) *SOA ASE injection* (0 dBm SOA input power, 200 mA drive current, -2 dBm ASE injection power) (c) *SOA ASE modulation* (0 dBm SOA input power, 200 mA drive current).

an OC-48 optimized receiver module. Note that a polarized ASE source was required due to the polarization sensitivity of the $\mathrm{LiNbO_3}$ modulator used in these experiments. We emphasize that while the same SOA was used in each system, the amplifier operating point was optimized in terms of input power, polarization and drive current in order to ensure best performance for each configuration. Eye quality of the *SOA ASE modulation* approach was seen to be unaffected by changes in the polarization state of the input spectrum-slice.

III. RESULTS AND DISCUSSION

Q measurements and corresponding eye diagrams for the back-to-back systems are given in Fig. 2. For the single channel systems analyzed here, intensity smoothing of the spectrum-slice prior to modulation (*SOA at the transmitter*) provides by far the best noise suppression. For a constant average detected power, it gives the largest eye opening with an intensity limited Q of 11.75 (BER $\approx 10^{-32}$). Introducing the saturated SOA prior to modulation has the added benefit in that the amplifier can be used as a booster and modulator while avoiding patterning effects. However, employing the SOA at the receiver also significantly improves the signal quality relative to the no-SOA case, allowing a Q of 8.2 (BER $\approx 10^{-16}$, extrapolating), and 7.2 (BER $\approx 10^{-13}$) at a received power of 0 dBm for the *ASE modulation* and *ASE injection* techniques respectively.

An accurate measure of system performance should however include the effects of multiple channels, including varying channel spacing and slice widths. The superior performance recorded in Fig. 2 for the *SOA at the transmitter* approach does not include previously reported post-SOA spectral filtering effects that arise as a result of channel selection at the receiver [9]. We have shown that in addition to the spectral broadening produced at the SOA output, the nonlinear signal processing that occurs within the saturated SOA gives rise to intensity correlations between the various frequency components propagating through the amplifier. Spectral filtering at the demultiplexer reduces these correlations resulting in decreased system performance. This is depicted in Fig. 3 where single channel Q measurements for the *SOA at the transmitter* configuration are shown as a function of receiver filter width. A 0.8 nm receiver filter width decreases system performance to approach that of the *SOA ASE modulation* technique, while a 0.6 nm filter yields performance comparable to that of the *ASE injection* approach. It should be noted that these filtering effects can be significantly minimized by careful selection of input slice width and channel separation. In contrast, with the *ASE injection* and *ASE modulation* techniques, channel selection occurs prior to the nonlinear signal processing, thus avoiding the undesirable effects of post-SOA filtering, albeit at lower system performance.

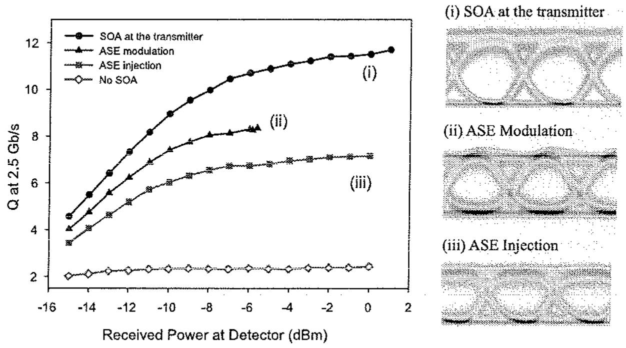

Fig. 2. Single channel back-to-back Q measurements (with no channel selection/filtering at receiver) and corresponding eye diagrams at an average power of -6 dBm. The received power for the ASE modulation technique was limited by the total output backward ASE of the SOA.

Q measurements for all three techniques after propagation through 15 km of fiber is shown in Fig. 4. For a length of 15 km, the group delay experienced by a spectrum-slice of 3 dB width 0.24 nm is ~61 ps, resulting in a pulse broadening of ~15% for a 400 ps (bit period at 2.5 Gb/s) data bit. Thus we would expect minimum system penalty due to the limited pulse broadening. This is indeed true for the

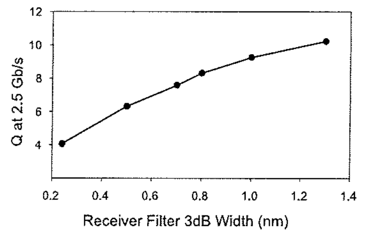

Fig. 3. Single channel Q at 0 dBm for *SOA at the transmitter* as a function of receiver filter width. Slicing filter width is 0.24 nm.

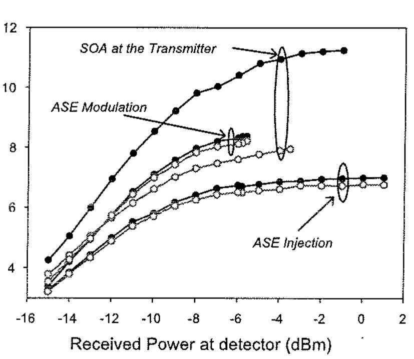

Fig. 4. Single channel Q measurements back-to-back (solid circles) and after 15 km of fiber (hollow circles) for all three techniques.

ASE modulation and *ASE injection* techniques. On the other hand, the SOA at the transmitter suffers a distinct performance penalty as the Q decreases from 11.75 to ~8 for an average detected power of 0 dBm. This signal degradation is a result of the dispersion-induced temporal misalignment of the spectral components of the intensity-smoothed light. The temporal misalignment counteracts the noise suppression of the SOA by reducing the intensity correlation between the different frequency components of the spectral slice [9]. It should be noted however, that this dispersion penalty can be eliminated by conventional dispersion compensation techniques.

An interesting point of contrast between using the SOA at the transmitter or at the receiver is in the manner in which performance improvement is achieved. Intensity smoothing of the CW signal prior to modulation increases the SNR of the transmitted signal. In comparison, when using the saturated SOA at the receiver, the extent of achievable performance improvement is limited in that if the transmitted signal is too noisy, the data cannot be recovered; i.e. noise suppression is ineffective if the resulting intensity smoothed signal has the incorrect logical bit value. Thus the SOA at the receiver techniques are not suitable for transmitted signals with high levels of intensity noise (e.g. very narrow spectrum-slices). This limitation does not apply if the noise suppression is performed prior to modulation, as in the *SOA at the transmitter* configuration.

We have also shown that the effects of post-SOA spectral filtering can be considerably reduced by optimized device design [9], giving advantage to the far superior noise suppression offered by the *SOA at the transmitter*. In comparison, incorporating SOA-based noise suppression at the receiver avoids the negative effects of spectral filtering and dispersion. It is also clear from our results that employing *ASE modulation* achieves better performance with lower system complexity than *ASE injection*, which requires an additional source at the receiver. It is also to be appreciated that a single-port SOA is sufficient for the *ASE modulation* technique, which as discussed in [5] can allow noticeable reduction in amplifier fabrication costs. Further cost reductions could be achieved by employing a directional coupler in place of the circulator (see Fig. 1(c)), with a slight penalty in receiver sensitivity.

IV. CONCLUSIONS

We have presented an experimental study into the benefits and drawbacks of three different spectrum-slicing approaches employing SOA-based intensity noise suppression. The saturated *SOA at the transmitter* provides the best noise suppression and back-to-back single channel performance of the techniques investigated. Although this approach is susceptible to dispersion and post-SOA filtering effects (e.g. at the demux), these multi-channel performance penalties can be reduced by optimized system and device design [9]. An optimized SOA structure, together with its advantage as a modulator and booster amplifier, has potential in delivering superior performance at reasonable cost for spectrum-sliced PONs. However, employing receiver based intensity noise suppression offered by the *ASE modulation* technique has the advantage of avoiding dispersion and post-SOA spectral filtering effects, while still providing very good signal quality. Using a single port SOA results in lower packaging costs, yielding additional advantages for cost sensitive end-user services. Thus the *ASE modulation* technique may provide better value for last-mile access applications where reduced system complexity could outweigh the comparative disadvantage in total noise suppression.

REFERENCES

[1] Chung et al., "SBS Limitation on a Spectrum-Sliced Fiber Amplifier Light Source," *Proc. Conf. on Optical Fiber Comm. (OFC 1995)*, pp. 33-34,1995.

[2] G.J. Pendock, and D.D. Sampson, "Transmission Performance of High Bit Rate Spectrum-Sliced WDM Systems," *J. Lightwave Technol.*, Vol. 14, pp. 2141-2148, 1996.

[3] S.-J. Kim et al., "Intensity Noise Suppression in Spectrum-Sliced Incoherent Light Communication Systems Using a Gain Saturated Semiconductor Optical Amplifier," *IEEE Photon. Technol. Lett.*, Vol. 11, pp. 1042-1044, 1999.

[4] Kim et al., "Intensity Noise Suppression of 2.5 Gb/s Spectrum-Sliced Incoherent Signal Using a Gain-Saturated SOA Injected by Broadband Light," *Optoelect. and Comm. Conf. (OECC 2004)*, pp. 46-47, 2004.

[5] T. Yamatoya and F. Koyama, "Optical Preamplifier Using Optical Modulation of Amplified Spontaneous Emission in Saturated Semiconductor Optical Amplifier," *J. Lightwave Technol.*, Vol. 22, pp. 1290-1295, 2004.

[6] Menif et al., "Error-Free Transmission for Incoherent Broad-Band Optical Communications Systems Using Incoherent-to-Coherent Wavelength Conversion," *J. Lightwave Technol.*, Vol. 23, pp. 287-294, 2005.

[7] G. P. Agrawal, *Fiber-Optic Communication Systems*, Wiley, 2002.

[8] McCoy et al., "Comparative Study of Spectrum-Sliced Incoherent Light Systems Employing SOA-Based Noise Suppression," *Proc. Conf. on Optical Fiber Comm. (OFC 2006)*, accepted.

[9] McCoy et al., "Noise Suppression of Incoherent Light Using a Gain-Saturated SOA: Implications for Spectrum-Sliced WDM Systems," *J. Lightwave Technol.*, Vol. 23, pp. 2399-2409, 2005.